U.S. PATENT APPLICATION

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Invention: RECONFIGURABLE PARASITIC CONTROL FOR ANTENNA ARRAYS
AND SUBARRAYS

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SPECIFICATION

RECONFIGURABLE PARASITIC CONTROL FOR
ANTENNA ARRAYS AND SUBARRAYS

RELATED APPLICATIONS

[0001]   This is a continuation-in-part of commonly assigned application 10/206,101

filed July 29, 2002 entitled "A Small Controlled Parasitic Antenna System and Method for

Controlling Same to Optimally Improve Signal Quality" and naming Thomas L. Larry as

sole inventor.

BACKGROUND OF THE INVENTION

1.   Field of the Invention

[0002]   The present invention relates to the field of antennas. Specifically, it relates to

the control (including beam and null steering and tuning) of phased arrays and subarrays by

using parasitic control elements in the aperture of each individual antenna element in the

array.

2.   Related Art

[0003]   Array antennas refer to the class of antennas which are formed by phase-

coherent combining of the outputs from multiple stationary antenna elements. The array

antenna's spatial beam pointing characteristics are determined by the positions of the

individual radiators (elements) and the amplitudes, phases, and time-delays of their

radiation. The amplitudes, phases, and time-delays are, in general, controlled by the

excitation of the individual antenna elements within the array. The antenna array

characteristics are also controlled, and usually limited, by the properties of the individual

elements in the antenna array and the way in which they interact with each other. These properties include the frequency properties of the individual elements as well as the element gain patterns.

[0004]   In many cases, antenna arrays are subdivided into smaller arrays known as subarrays. Subarrays, when used, are constructed for ease of mechanical construction as well as for providing a way to minimize the amount of feed and phase control or time-delay structure needed to control the radiation of the individual elements.

[0005]   The versatility of phased array antennas is convincingly evidenced by their broad range of military and commercial applications including communications, radar, and electronic countermeasures. For all of their advantages, however, performance of phased array antennas is limited. Phased arrays are usually limited in the range of angles over which they can effectively steer a beam without significant losses in overall system gain.

[0006]   There are two primary reasons for this. These can be seen by first considering an array made up of N individual antenna elements. The overall array gain for this N-element system in the direction θ can be written (in dBi) as,

$$G(\theta) = 10 \log(N) + g(\theta) + 10 \log(1 - |\Gamma(\theta)|^2) - \alpha \qquad (1)$$

where g(θ) is the embedded gain pattern for an individual antenna element in the direction θ, Γ(θ) is the active reflection coefficient, and α represents losses in the beam forming network that are independent of Γ(θ). Equation (1) presumes the array is being steered in the θ direction. Thus, the expression does not represent the array pattern but, rather, it represents the gain in the scan direction. In particular Γ(θ) is the effective reflection coefficient when the individual array elements are phased so as to produce a beam in the θ

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direction. Also g(θ) and Γ(θ) are assumed to be the same for all of the N elements. This latter assumption is an approximation. In practice there will be element-to-element differences. Indeed, for applications involving moderate sized arrays the element-to-element variations in g(θ) may have significant impacts on the array performance.

[0007]   However, for this example we consider (1) to be a reasonably accurate summary of the array characteristics. Suppose $\hat{G}$ is the desired system gain given by a requirement or specification. This specification can be met at angles for which,

$$g(\theta) + 10\log(1 - |\Gamma(\theta)|^2) \geq \hat{G} - 10\log(N) + \alpha \qquad (2)$$

If g(θ) gets too small and/or |Γ(θ)| gets too close to 1, then condition (2) cannot be satisfied. Thus, presuming that the losses α are acceptable, drop off in g(θ) and increase in |Γ(θ)| are the two basic factors that limit the coverage of the array. For certain steer angles the mutual coupling among the elements can become substantial. This leads to an increase in |Γ(θ)| and, consequently, the system may not be able to meet specifications for that range of angles.

[0008]   In other words, the element gain characteristics as a function of angle and frequency is a fundamental limit in range of angles the array can be scanned to and the frequencies at which it will operate.

[0009]   Introducing reconfigurability at the individual antenna element level leads to the possibility of much higher performance in gain, pattern shaping, and frequency agility of the individual array elements which then leads to enhanced overall array performance. The purpose of reconfiguration to the array is to adapt the gain characteristics of the individual antenna elements so as to get the maximum possible performance from the antenna system.

[0010]   Reconfiguration can be used to expand the range of operational functions in a

number of ways. First, the embedded array elements can be frequency tuned, and bandwidth

can be improved by using reconfiguration to broaden the bandwidth of the embedded

elements. In addition, for high gain arrays, beam squint is usually the limiting factor on

instantaneous bandwidth. Reconfiguration can alleviate this problem by providing control of

the element phase centers. Scan coverage can be improved and scan blindness alleviated by

controlling the embedded antenna gain patterns of the elements as well as by providing

control of the active impedance as the beam is scanned. Applying limited phase control to

the elements themselves can alleviate some of the complexity of the feed manifold.

BRIEF SUMMARY OF THE INVENTION

[0011]   The invention disclosed here provides reconfigurable antenna arrays designed

by selectively placing load impedances in the aperture of the individual antenna elements

within an antenna array. These loads can be controlled to change the operational

characteristics of the individual antenna element. These characteristics include directivity

control, tuning, instantaneous bandwidth, and RCS. By controlling the properties of the

individual antenna elements within the array, the performance properties of the array can be

changed.

[0012]   Specifically, this invention builds on parent application No. 10/206,101 that

describes the use of loaded parasitic components within the radiating aperture of an antenna

element for the purpose of controlling the RF properties of the antenna element. It also

describes the use of a feedback control subsystem that is part of the antenna system which

adjusts the RF properties of the parasitic components based on some observed metric of the received waveform. This antenna system is referred to as a controlled parasitic antenna (CPA). By using a feedback control subsystem to control the electromagnetic properties of the antenna aperture, this antenna system can provide multifunctionality and / or mitigate problems associated with reception of an interfering signal or signals within a very compact volume.

[0013] In the present invention, by controlling reactive loads or switches attached to a parasitic element collocated with the individual radiating elements within an array or a subarray we can control the frequency properties of the array can be controlled and the scan angles can be increased. This approach holds promise for overcoming many of the limitations of current phased arrays.

[0014] One way of increasing the coverage of the array is by the use of reconfigurable elements. Such elements make use of one or more active control devices embedded in the aperture (specifically in parasitic elements in the aperture) of the individual radiating elements within the array. The impedance of the control device or devices would depend on the value of an applied bias voltage V or voltages (V_1, V_2, ...). A change in bias values would change the impedances and, consequently, the antenna properties of the element would change. This means that the embedded element gain and the active reflection coefficient become functions of V or (V_1, V_2, ...) as well as θ. That is, these factors in Expression (1) above can be expressed as $g(\theta, V_1, V_2, ...)$ and $\Gamma(\theta, V_1, V_2, ...)$. This disclosure teaches that it is possible to design reconfigurable elements so that the coverage of the array can be expanded considerably by varying the state of the elements.

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[0015]   It will also be shown that the implementation of two-state (switchable) devices as controls could be very effective for expanding the coverage of a phased array system. The bias voltages would only need to take on two different values (usually 0 volts and some other voltage that exceeds a switching threshold). The number of independent biases needed would depend on the number of two-state devices per element.

[0016]   The exemplary embodiment also addresses the loss of array gain that occurs in certain scan directions of an array that seeks to scan from end-fire to angles greater than 25-30 degrees from end-fire. Typically, for a given aperture the maximum achievable gain at angles of about 20° from end-fire is 2-3 dB less than what can be achieved at end fire or at larger scan angles (30° or more from end fire). This will be referred to as the gain depression problem. This problem is particularly acute for applications where a large scan angle range starting at end-fire is desired and the mid-range directions from 15-25 degrees are particularly important. The direction θ_D relative to end-fire at which this gain depression is most severe will be called the depression scan angle. The value of θ_D depends on the array size and the electrical length between array elements. This gain reduction can be due to reduced values of $g(\theta_D)$ or increased values of $|\Gamma(\theta_D)|$, or both at the scan depression angle. Significant increases in $|\Gamma(\theta)|$ for certain ranges of scan angles is common with phased arrays and is referred to as scan blindness. For such scan angles there is a significant drop in array efficiency. Reconfiguration can be effective in alleviating scan blindness problems. If this is done at the angle θ_D, the gain depression problem tends to persist due to depressed values in the embedded element pattern $g(\theta_D)$ at this angle. This disclosure

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demonstrates this problem and teaches potential ways of improving the gain depression problem.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017]   Figure 1 illustrates a basic block diagram for a single-element controlled parasitic antenna (CPA);

[0018]   Figure 2 provides a general block diagram for a single-element controlled parasitic antenna (CPA) element that might be used as an individual element in a phased array;

[0019]   Figure 3 illustrates a general representation of how the element pattern of an individual element in a phased array is controlled so the phased array can be scanned to that direction;

[0020]   Figure 4 provides a simplified phased array concept made up of N parasitically controlled elements;

[0021]   Figure 5 illustrates a simplified phased array concept made up of parasitically controlled elements all controlled form a single beamforming control unit and corporate fed into a transmit/receive module (which can also represent a single subarray for a larger array);

[0022]   Figure 6 illustrates a simplified phased array concept made up of parasitically controlled elements in N subarrays;

[0023]   Figure 7 provides a simple schematic of a generalized phased array made up of reconfigurable subarrays. Each subarray has a T/R module and a true time delay unit attached to it;

[0024]   Figure 8 illustrates a Notional reconfigurable element with loaded parasitic elements;

[0025]   Figure 9 illustrates a 3 element array of loaded parasitic elements;

[0026]   Figure 10 is a photograph of the three element array of loaded parasitics;

[0027]   Figure 11 provides measured reflection coefficient of center element of 3 element parasitic array;

[0028]   Figure 12 depicts the computed reflection coefficient of center element of 3 element parasitic array;

[0029]   Figure 13 illustrates the embedded element gain pattern of center element of 3 element parasitic array at 5.9 GHz;

[0030]   Figure 14 illustrates a reconfigurable element with loaded parasitic loop;

[0031]   Figure 15 illustrates beam scans for an 8 element array of loaded parasitic elements;

[0032]   Figure 16 illustrates beam scans for a 16 element array of loaded parasitic elements;

[0033]   Figure 17 illustrates beam scans for a 24 element array of loaded parasitic elements;

[0034]   Figure 18 illustrates beam scans for a 32 element array of loaded parasitic elements;

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[0035]   Figure 19 illustrates beam scans for a 40 element array of loaded parasitic

elements;

[0036]   Figure 20 illustrates beam scans for a 48 element array of loaded parasitic

elements;

[0037]   Figure 21 illustrates a dual polarized element with loaded parasitic loops;

[0038]   Figure 22 depicts a section of the network diagram of the dual polarized array

showing four of the fed and controlled elements;

[0039]   Figure 23 illustrates beam scans for a 16 element array of dual polarized

elements;

[0040]   Figure 24 illustrates an alternate exemplary configuration for parasitic control

of an antenna element in an array. In this configuration the controlled parasitic Microstrip

elements are placed between the fed (driven) element and the ground plane;

[0041]   Figure 25 illustrates another view of the controlled parasitic element of Figure

24 (wherein the parasitic element control lines are not shown in this view for clarity); and

[0042]   Figure 26 illustrates how the parasitically controlled element of Figures 24

and 25 can be placed in a phased array.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0043]   **Figure 1** shows a schematic representation of a single-element controlled

parasitic antenna (CPA). The CPA (as taught in parent application 10/206,101) makes use

of a feedback loop to adaptively determine the value of the control signal that will control

the parasitic control device placed in or to the parasitic control element in the aperture of the

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antenna. This feedback loop contains a controller which has an adaptive logic unit, a control signal circuit, and the control device. The control device can be either a two state switch, which usually manifests itself as a two-state reactance, or it can be a continuously variable device (or multiple devices) such as a variable capacitor or varactor used by itself or as part of a control circuit. The feedback loop can tap the output either before (pre) or after (post) the receiver.

[0044]   There may be situations where both pre and post feedback loops are used. Examples might be where a return loss (VSWR) signal is measured after the matching network and is fed into the adaptive control unit so that the antenna may be retuned to minimize the VSWR. At the same time a receiver error measurement (such as bit error rate) might be made and sent to the adaptive control unit so that the gain pattern may be controlled to minimize the received error.

[0045]   **Figure 2** shows a schematic representation of the most general configuration of a single-element controlled parasitic antenna (CPA) element that might be used as one of several elements in a phased array. Because this is one of N elements in a phased array, it is necessary to control the phase of the individual element in order to steer the beam of the array. **Figure 2** shows that a phase control unit is controlled by a beam control unit which may be exterior to the individual element. In addition, the beam control unit also can have input into the parasitic control logic unit. In this way, the parasitic control device can be modified to optimize the gain of the antenna element such that as the phased array is scanned, the element pattern will support it. **Figure 3** represents this concept.

[0046]   The semicircular dotted line in **Figure 3** represents the envelope of the hemispherical scan pattern that we would ideally want to scan a phased array over. Normally, the element pattern within a phased array will not support such a scan envelope. However, if the element pattern can itself be scanned as represented by the controlled element patterns (#1, #2, #3) then the array can then be scanned in the desired directions. In the invention disclosed here, the beam control unit (represented in Figure 2) would control the phasing of the individual element as well as send a signal to the parasitic control unit which would then set the parasitic control device to the appropriate setting to control the pattern of the driven element.

[0047]   **Figure 4** shows a phased array configuration made up of N single-element controlled parasitic antennas. In this configuration, there would be a central beamforming control unit to control the steering of the array by controlling the phase of each element as well as controlling the gain pattern of each of the N individual antenna elements via the parasitic controller. The individual elements can have the local feedback control as shown in **Figure 3**. The Beamforming Control Unit controls not only the phase of each individual element but it also can control the loading of the parasitic elements associated with each element in the array. This same control can also be used to adjust the magnitude of each element by way of the parasitic control element.

[0048]   **Figure 5** shows a simplified phased array configuration made up of parasitically controlled elements which are all controlled from a single beamforming control unit. A corporate feed system is used to feed the transmit / receive (TR) module unit from each of the elements. Feedback to the Beamforming Control Unit can come from the T/R

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Unit. In addition individual element control can come from feedback within each element but is not shown in **Figure 5** to keep the drawing simple. **Figure 5** can also represent a single parasitically controlled subarray within a larger array. This concept is shown in **Figure 6.**

[0049]   In **Figure 6** the beamforming for the array is represented as either being done using true-time delay or done via digital beamforming. In either case the, each subarray can still be parasitically controlled to shift the individual element's gain pattern or to retune the antenna element. **Figure 7** presents an alternative depiction of the reconfigurable subarray concept.

[0050]   **Figure 8** shows a notional picture of one type of element that was initially built and tested to quickly demonstrate the concept of this invention. This array of reconfigurable antenna elements can be made as either microstrip elements above a ground plane or simply as bent wires above a ground plane. This element makes use of an active line that is connected by a via (feed point in the picture) to the source. Each driven element also has two parasitic lines that have a connection to the ground plane. For a reconfigurable design these connections would be connected to the ground plane through an electronic switch device. For this test there was no such device. Instead a manual method using silver paint was used to quickly test the concept.

[0051]   **Figure 9** shows a notional drawing of a 3-element array of these parasitic elements that was fabricated. **Figure 10** is a photograph of the array that was actually built. The ruler indicates the size of the array which is a little more than 2 inches in length. Our primary goal in this initial study was to demonstrate that the embedded element pattern $g(\theta)$

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and the active reflection coefficient $\Gamma(\theta)$ can be significantly altered using reconfiguration. This work has focused entirely on two-state control. That is, the elements can be in either of two states. Whether or not a two-state element provides sufficient reconfiguration control depends on eventual application. Some applications are known to require a very large number of element states. Because of the limited nature of this work, the antenna systems built were very small in terms of the number of elements (3 elements). Our primary goal was simply demonstrate that reconfiguration can have a significant effect on the pattern $g(\theta)$ and reflection coefficient $\Gamma(\theta)$. This has been accomplished. Future work will focus on the design of reconfigurable elements and arrays that can achieve optimum performance in accordance with a particular set of design criteria.

[0052]   The measurements shown in **Figure 11** were performed on the 3-element array of loaded parasitic elements shown in **Figure 10**. The figure is actually a picture of the network analyzer screen, which shows the measured reflection coefficient (return loss) at the center element port for both the shorted (yellow curve) and open (green curve) states of the elements. The frequency scale is 4 to 9 GHz in steps of 0.5 GHz. For the shorted state the antenna has its best tuning at 5.6 GHz and the open state is best tuned at 6.2 GHz. The reconfiguration of the element has clearly changed the tuning characteristics. However, there is still a common tuned band for both states, which approximately spans the 5 to 6 GHz range. **Figure 12** shows corresponding computed results for this case. There is a good comparison between the measured and modeled results.

[0053]   Upon examining **Figure 11** it is seen that the best common frequency (in terms of tuning) of the 2 states is at about 5.9 GHz. **Figure 13** shows the patterns that were

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measured at this frequency for both states. In the figure, 0° would correspond to end-fire and 90° is at broadside to the array. The broadside gain of the shorted state was used as the reference for these measurements. It is clear that reconfiguration has a significant impact on these patterns. Also, it seems clear that from the point of view of $g(\theta)$ that the open state is preferable near end-fire and that the shorted stated is preferable from about 30° to 70° from end-fire.

[0054] The initial study was aimed at showing that the use of controllable elements can be effective for expanding the coverage of a phased array system that is constrained to a certain aperture. The technology for accomplishing this is mature and control devices are available with substantial power handling capability. This limited effort has enabled us to demonstrate that reconfiguration can have a very significant impact on $g(\theta)$ and $|\Gamma(\theta)|$, which were discussed in the previous sections.

[0055] We performed a limited study to test the concept of switching the state of an element to alter its properties. The eventual goal would be to optimally design such elements in a manner that is favorable to the design of a phased array with substantially broader coverage than would otherwise be possible without the element reconfiguration. This test was limited in scope and focused primarily on laboratory demonstration and experimentation. Active switch devices and biases were not used, as would be the case in an actual application. Instead we built elements and arrays that could be manually switched between two different configurations. This manual switching was accomplished by using silver paint to short an otherwise open end of the element to the ground plane. The paint could be easily removed to restore the 'open state' of the antenna element or array of

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elements. These two configurations simulated two different element states that could be achieved by using an electronic switch. The properties of the elements were measured and/or computed for both states. In most cases we were able to make good comparisons between measurements and predictions. The results are encouraging and show that both the both the embedded patterns and active return loss can be significantly controlled using reconfigurable parasitic elements within the phased array.

[0056]   A reconfigurable array element that offers significant improvement with respect to the reconfigurable lines of the previous section is depicted with loaded parasitics in **Figure 14**.

[0057]   The element shown above has two parts. One is an active 'arm' (green) that connects to the feed port, which is basically a via through the ground plane. On either side of the active arm is a parasitic loop. Each end of one of these loops terminates at a port, which is also a via through the ground plane. Impedances can be applied at these latter ports. These load impedances affect the antenna characteristics of the element. Even though there are 4 load ports there were only two independent load values for the examples that are shown in this section. These are indicated in the above figure. For the studies to be shown these impedances were chosen to maximize the V-pol gain for various scan angles at 10.5 GHz.

[0058]   The reconfigurable loaded parasitic element of **Figure 14** provides significantly improved gain at high scan angles when compared with the reconfigurable loop of the previous section. It also maintains good end-fire gain. Thus, a single array of such elements can provide both the end-fire coverage as well as the high scan coverage. In

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Figures 15 to 20 are shown the main-beam patterns of various scan angles for arrays

varying in size from 8 to 48 elements. The loaded parasitic elements were used. The load

impedances were chosen to maximize the gain for each scan angle shown. These results

show the good end-fire gain (0 and 180 degrees) as well as good gain at higher (broadside)

scan angles. In **Figure 14** angle θ is measured from end-fire. The beam scan patterns are

asymmetric because the radiating element is asymmetric. The results also exhibit the fact

that there is a gain depression angle which moves towards end-fire as the array length

grows.

[0059]   An array based on the reconfigurable element of **Figure 14** can provide good

end-fire gain as well as good gain at higher scan angles. However, gain depression problem

persists. The next section examines a variation of this element that enables some

polarization control. This shows some promise of being able to significantly improve the

problem of gain depression.

[0060]   A reconfigurable array element that is a variation of the element shown in

Figure 14 is shown in **Figure 21**. This element consists of two active arms of the **Figure 14**

element. These active arms are orthogonal. Parasitic elements of the same size as the ones in

Figure 14 are also shown. For this element these parasitics are orthogonal. Each element

has two feed ports and four load ports. For the study shown in this section the feed ports

were combined using a pair of switches and a phase shifter. This enables control over the

polarization of the element. For the element shown above the active 'arms' (green) connect

to the feed ports. On either side of each active arm is a parasitic loop. Each end of one of

these loops terminates at a port, which is a via through the ground plane. Impedances can be

applied at these latter ports. These load impedances affect the antenna characteristics of the element. In this case all four load ports were allowed to have independent load values. These are indicated in the above figure. For the studies to be shown these impedances were chosen to maximize the total gain for various scan angles at 10.5 GHz. Note that this element allows for both V-pol and H-pol as well as combinations of these two basic polarizations.

[0061]   A 16-element array was modeled and **Figure 22** shows a portion of the feed and load networks. Note that for each element there is a pair of ideal switches SW1 and SW2 and a relative phase PS between the V-pol and H-pol feeds. Also for each element there are 4 load impedances Z1, Z2, Z3, and Z4. Each switch was allowed to be either on or off. The nth steering phase is indicated as φn. The set of variables SW1, SW2, PS, Z1, Z2, Z3, and Z4 were constrained to be the same for each element. For each scan angles these values were chosen to maximize the system gain.

[0062]   In **Figure 23** shows the main-beam patterns for the various scan angles that were used. These results should be compared with **Figure 16**, which shows the beam patterns of the 16 element array from the previous section. The dual polarized element shows enhanced gain at all scan angles when compared to the previous results. The polarization of the element varies from scan to scan. Gain depression is still noted near the end-fire direction but the magnitude of this depression is not as great as before. It also appears that the gain is somewhat better for the opposite end-fire direction when compared with **Figure 16**. This indicates that the dual polarized element should be oriented in the opposite direction to what is shown in **Figure 21**.

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[0063]   It was mentioned above that the switch values were variables in the

optimization for each scan direction. In most cases the optimization procedure chose both

switches to be on with some relative phase between the V-pol and H-pol feeds. The beams

for these scans are red in **Figure 16**. However, in a few cases the optimizer "turned off" the

V-pol feed in favor of the H-pol feed. These are shown as blue in the figure. It is interesting

to note that these correspond to the directions where the gain depression tends to occur. The

gains for these beams have a dominant H-pol component. This indicates that the gain

depression problem is related not only to the scan angle but also the polarization of the

elements. It appears that elements with variable polarization may provide a means of

mitigating gain depression.

[0064]   **Figures 24 and 25** present another possible implementation of a

reconfigurable parasitically controlled element that can be used in a phased array. In this

case a microstrip radiating (fed or driven) element is placed above the ground plane. This

fed element can take many different configurations. In the implementations of **Figures 24**

and 25 a simple three prong radiator is shown. The parasitically controlled elements are

placed between the fed element and the ground plane. Again, any number and shape of

parasitic elements can be used here. **Figure 26** shows how the single reconfigurable element

of **Figures 24 and 25** can be placed in an array of elements.

[0065]   Reconfiguration of parasitically controlled elements in a phased array can be

used to expand the range of operational functions in a number of ways. First, the embedded

array elements can be frequency tuned, and bandwidth can be improved by using

reconfiguration to broaden the bandwidth of the embedded elements. In addition, for high

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gain arrays, beam squint is usually the limiting factor on instantaneous bandwidth. Reconfiguration can alleviate this problem by providing control of the element phase centers. Scan coverage can be improved and scan blindness alleviated by controlling the embedded antenna patterns of the elements as well as by providing control of the active impedance as the beam is scanned. Applying limited phase control to the elements themselves can alleviate some of the complexity of the feed manifold.

[0066]   A presently preferred method of designing the reconfigurable antennas of this invention is to selectively place controlled parasitic elements in the aperture of each of the antenna elements in the phased array. The parasitic elements can be controlled to change the operational characteristics of the antenna element. The parasitic elements are controlled by either switching load values in and out that are connected to the parasitic elements or are controlled by applying control voltages to variable reactance circuits containing devices such as varactors. The parasitic elements can be controlled by the use of a feedback control subsystem that is part of the antenna system which adjusts the RF properties of the parasitic components based on some observed metric. The controllable characteristics include directivity control, tuning, instantaneous bandwidth, and RCS.

[0067]   These as well as other objects and advantages of this invention will be apparent to those skilled in the art upon careful study of this entire application. The appended claims are intended to cover not only the described exemplary embodiments of this invention but also all modifications and variations thereof apparent to those skilled in the art in light of the teachings of this patent application.